In this article, dynamic behaviors of a carbon fiber reinforced composite bi-stable laminate are studied. The ABAQUS/CAE is used to simulate the dynamic response of the bi-stable laminate under harmonic foundation excitation at the center. Subspace iteration method is considered to analyze the mode of dynamic snap-through. Base on the implicit direct integration method, time domain response and frequency domain response of the system are achieved. Considering the dissipative effect of Rayleigh damping, the potential energy curve is used to describe the variety of strain energy during the process of snap-through. The factors affecting the dynamic snap-through performance of the bi-stable laminate, including the curing temperature, structure sizes, layup conditions and dissipation factors, are discussed analytical solutions. Under the influence of multi-parameters, a series of single-well vibrations and cross-well vibrations is fully displayed.

Keywords: bi-stable laminate, non-linear vibrations, dynamic snap-through, cross-well vibrations

1. Introduction

The main advantage of bi-stable composite laminates as a morphing structure is the fact that they exhibit more than one natural equilibrium position at which the structure can settle without demanding an external power. The other interesting feature is that the bi-stable or multi-stable structure needs a very small energy input to end up with a relatively large deflection, realized as a jump phenomenon, which moves the structure from one equilibrium position to another. These two features led to the conclusion that bi-stable structures can be energy-efficient morphing structures. [1-5]. Much of researches carried out that the two cylindrical shapes of a bi-stable composite laminates plate structures based on the classical lamination theory [6-8]. Hyer et al. [9, 10] developed a geometrically new theory to investigate the temperature-curvature relationship of unsymmetrical square laminates. Moreover, Brampton et al.[11] and Fernandes et al. [12] presented modelling sensitivity analysis, the numerical result reveal significant sensitivities of the laminate to Young’s moduli, transverse thermal expansion coefficients, ply thickness and the temperature change from the elevated cure temperature. Most of the studies on the bi-stable
composites have focused on the static characteristics of structure and linear dynamic behaviour [13-15]. However, the transition between two stable states for bi-stable plates is strongly nonlinear in nature, which is known as snap-through mechanism. Kevin et al. [16] applied load–deflection measurements to study the phenomena observed in the large scale bifurcation of unsymmetrical composite plates. Andres et al. [17, 18] presented a low order model to capture the nonlinear dynamics of a bi-stable composite plate and studied morphing control for bi-stable [19]. David et al. [20] compared the theoretical and experimental investigation of a bi-stable composites laminate using piezoelectric element method to perform broadband vibration. In this paper, the nonlinear dynamics of a centrally supported bi-stable composite laminates are investigated by using ABAQUS/CAE. During the simulation, the computational non-convergence caused by the strong nonlinearity of dynamic snap-through is considered. Rayleigh damping is considered to study the dissipation of potential energy during the snap-through. The influence of material properties and structural parameters on the dynamic snap-through frequency of structures is studied. The nonlinear vibration characteristics of the system are studied under foundation excitation.

2. Model properties and solution technique

A series of Graphite-Epoxy T300/934 rectangular laminates with the [0/90]_T stacking sequence and different aspect ratios have been studied. The laminates were subjected to a temperature gradient from 180°C to 25°C, corresponding to the cure and room temperatures, respectively. Table 1 describes the mechanical and geometrical characteristics of the laminates. The laminates were modeled by ABAQUS/CAE where the type of curved shell elements were considered. The only restraint applied was at the middle area of the laminate, where all degrees of freedom were restricted.

| Table 1. Properties of Gr.-Ep (T) (T300/934) unidirectional lamina. |
|-----------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|
| \( E_{11} (Gpa) \) | \( E_{22} (Gpa) \) | \( G_{12} (Gpa) \) | \( G_{13} (Gpa) \) | \( G_{23} (Gpa) \) | \( v_{12} \) |
| 131 | 10.342 | 6.894 | 6.205 | 6.205 | 0.22 |
| \( t_{ply} (mm) \) | \( v_{13} \) | \( v_{23} \) | \( \alpha_1 (10^{-6} / \degree C) \) | \( \alpha_2 (10^{-6} / \degree C) \) | \( \rho (Kg/m^3) \) |
| 0.125 | 0.22 | 0.22 | -0.167 | 15.6 | 1500 |

To simulate the plate’s stable configurations under the temperature effect, the following steps have been taken in the FE model:

- In the first step, a small force in z-direction (as imperfection) has been applied on four corners of the plate while the temperature of the plate decreases 5°C (from 180°C to 175°C).
- In step 2, the applied forces in step 1 are removed, and the temperature decreases from 175°C to 25°C.
2.1 Modal analysis

The free vibration modes of two stable cylindrical states and one unstable critical saddle state are studied using subspace iteration method. The result is shown in Figure 2.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Stable 1</th>
<th>Unstable</th>
<th>Stable 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>First-order modal</td>
<td>![Image]</td>
<td>![Image]</td>
<td>![Image]</td>
</tr>
<tr>
<td>Freq=11.517</td>
<td>Freq=3.7893</td>
<td>Freq=11.408</td>
<td></td>
</tr>
<tr>
<td>Second-order modal</td>
<td>![Image]</td>
<td>![Image]</td>
<td>![Image]</td>
</tr>
<tr>
<td>Freq=16.079</td>
<td>Freq=9.2771</td>
<td>Freq=16.064</td>
<td></td>
</tr>
<tr>
<td>Third-order modal</td>
<td>![Image]</td>
<td>![Image]</td>
<td>![Image]</td>
</tr>
<tr>
<td>Fourth-order modal</td>
<td>![Image]</td>
<td>![Image]</td>
<td>![Image]</td>
</tr>
<tr>
<td>Freq=22.780</td>
<td>Freq=51.394</td>
<td>Freq=22.710</td>
<td></td>
</tr>
</tbody>
</table>

Figure 2: First four orders modes and frequency response of bi-stable laminates

The first and second mode is that the plate rotate along the X and Y axes, respectively. And the third mode the four corners of the plate vibrates in the same direction. The fourth order mode of laminated plate is four corners every two opposing motions. The next study focused on the condition of the dynamic snap-through of the laminated plate which is related to resonance frequency.

2.2 Dynamic snap-through

The bi-stable laminates are subjected to the central region's foundation displacement excitation. The value of external excitation frequency is set to each order resonance frequency of the bi-stable laminates. Dynamic analysis within a definite range of resonance frequencies of system response characteristics were studied using time-domain analysis method. In order to obtain the time-domain response, implicit direct integration method is used here.
3. Results and discussion

The vibration form of the system with the change of the external excitation amplitude near the third order is studied. The result is shown in Figure 3.

(a) The periodic vibration when excitation amplitude is 0.001

(b) The periodic vibration when excitation amplitude is 0.002

(c) The dynamic snap-through when excitation amplitude is 0.0041
Figure 3: Waveforms and phase diagrams of systems that vary with external excitation

When enlarging the amplitude of the transverse excitation, the system becomes more unstable and multi-periodic and chaotic motions occur besides the periodic motion.

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